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Numerical Simulation and Analysis of Heat Treatment of Large-scale Hydraulic Steel Gate Track*

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(Abstract) While large-scale steel gate track is subjected to huge wheel pressure, its surface will be under tremendous local contacting stress. As an important process in the track manufacturing process, heat treatment can enhance the external strength and hardness as well as the internal toughness. Utilizing the high pressure gate in three gorges dam as engineering background, With finite element method, the temperature field through quenching process is simulated. With the mathematical model based on TTT curve (Time, Temperature, Transformation), through programming on ANSYS software, the metallurgical structure field and hardness distributions are obtained. Thereby the relationship between heat treatment processing parameters and the material mechanical proprieties is established. These results suggest that the redesigned heat treatment process can meet the application requirements, and are valuable for guiding the optimization of track heat treatment process.

Keywords: heat treatment; hardness and strength distribution; numerical simulation of microstructural field; quenching temperature field

1. INTRODUCTION

Large scale steel gate track and wheels are usually made of medium carbon alloy steel, which should have gone through heat treatment. However, this heat treatment could cause residual stress and mechanical properties variation along depth. All these factors have influences on the bearing capacity of track and wheels. The design method of track-wheel contact strength in current Chinese code[1] is based on Hertz linear elastic theory, which is limited to non-friction and ideal elastic homogeneous body. Due to great changes of mechanical properties after heat treatment, using the mechanical properties before heat treatment to design the track and wheel does not conform to actual situation. Hardness and strength distribution can be obtained through numerical simulation of heat treatment, which can provide a basis for calculation of track-wheel contact strength.

Designing large hydraulic track heat treatment processes involves a variety of complex factors, making it difficult to be analyzed theoretically. In practice, these parameters are usually determined by engineering experience or measuring test results. Traditional trial-and-error retooling procedures may result in high cost due to low yield of fabricated rails. As a kind of computer aided process design method, numerical simulation of quenching process can optimize process design and reduce the rejection rate, thus improve the work efficiency apparently.

Numerical simulation of quenching process abroad first started in 1970s. Swedish scholars B. Hildenwall et al.[2] first successfully solved the problem how to predict the transformed volume using TTT curve with the concept of virtual time and the superposition principle. As for numerical simulation of microstructure field during quenching, two kinds of mathematical models have been established, both of which can predict the microstructure field conveniently. Most multi-physical field FEM (finite elements method) softwares such as MSC, ABAQUS, ANSYS, can not be used to calculate microstructure distribution directly, due to lack of microstructure field[3].

2. SIMULATON OF QUENCHING THERMAL FIELD

Large scale steel gate track is buried into the pier concrete, too hard to replace in case of failure. Therefore, it should be ensured that the track mechanical properties are better than those of wheels, so that wheels could fail before the track does[4]. Setting three gorges dam high pressure gate as engineering background, we designed the heat treatment method and processing parameters, and then simulated thermal field with ANSYS programm. We selected 35CrMo for wheel and 42CrMo for track, both of which have high quenching degree, great toughness, small deformation after quenching, high creep strength under high temperature, and are suitable for large-section workpieces.

According to the code[5], when subjected to design wheel load of 4100kN, the external hardness of the wheel should reach up to 430HB, the external hardness of track should be 50HB higher than that of the wheel. However, due to lack of

*Numerical Simulation and Analysis of metallographic structure field

theoretical guidance, quenching and high temperature tempering was designed to put onto the workpiece, making the hardness of track and wheel becomes 333HB and 277HB, respectively. The requirements of above code was not met. Previous analysis conducted by us[6] on processing parameters of heat treatment revealed that the hardness requirements of track could be met by resetting the heat treatment processing parameters as holding at 850℃ for 2hr, quenching in 19m·min^{-1} N32 oil for 20min, and then 180~200℃ tempering for 3hr.

The track finite element model is shown in **Figure 1**. As boundary condition in FEM simulation, the surface synthetical heat transfer coefficient has significant influence on the precise simulation of thermal field. This paper adopts the conclusions made by Chen, N.L. et al.[7], where surface transfer coefficients at different flow velocities were obtained via experiment and calculation with inverse heat conduction method. The synthetical transfer coefficients used are shown in **Table 1**, latent heat was considered according to enthalpy. The previous temperature field FEM simulation conducted by us[6] suggests, after quenching, the temperature curves at the points on line 1 in **Figure 1** (depth=0, 1.7, 3.3, 5, 10, 20, 50mm) is shown in **Figure 2**, while the mean cooling speed at 700℃ at these points is shown in **Figure 3**.

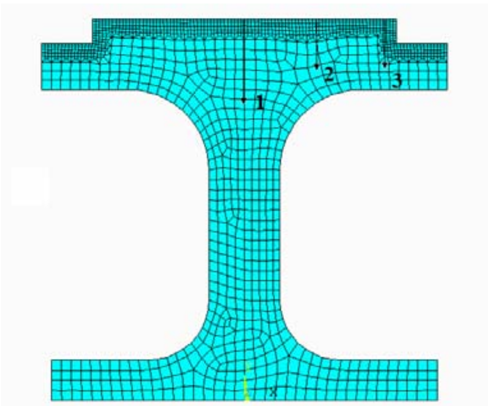

Figure 1. Finite element model of the track

Table 1. 19m·min^{-1} N32 oil quenching heat transfer coefficient

Temperature	20-300	400	500	600	700	800	900
Heat transfer coefficient	500	1200	1680	1400	920	600	0

Note: the unit of temperature is ℃, unit of Heat transfer coefficient is W/(m^{2}K)

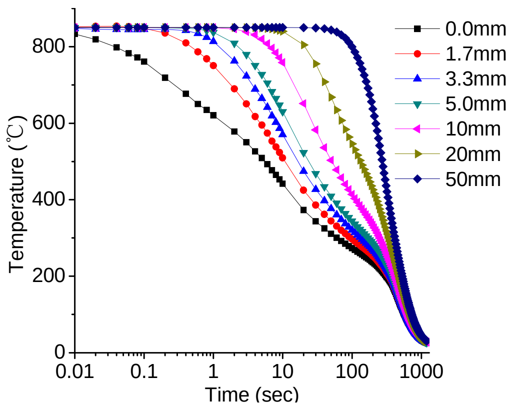

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Figure 2. Cooling curves at different depths

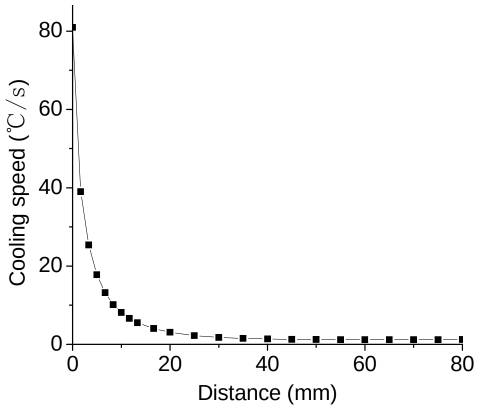

Figure 3. Average cooling rate at 700℃

3. MATHEMATIC MODEL OF MICROSTRUCTURE FIELD CALCULATION

Two kinds of mathematic models have been established for deducing microstructure field from temperature field, namely mathematic model based on TTT curve (Time, Temperature, Transformation), and mathematic model based on CCT curve (Continuous Cooling Transformation). For large scale steel gate track, the volume of martensite has significant influence on hardness and strength, therefore mathematic model based on TTT curve is adopted in this paper.

3.1. mathematic model based on isothermal transformation curve

The transformation towards pearlite and bainite are both diffusive phase transformation. The Avrarmi formula which describes the transformation volume is:

$$V_{\mathrm{P,B}} = 1 - \exp[-b(\Delta t)^n] \tag{1}$$

where, b and n are parameters only determined by temperature. The transformation towards martensite is non-diffusive transformation. Usually adopt Koistinen-Marburger model describe the transformed volume as:

$$V_{\mathrm{M}} = 1 - \exp[-\alpha(M_s - T)] \tag{2}$$

where α and M_s are both constants determined by material type.

The actual temperature variation is continuous cooling, rather than isothermal variation. By applying Scheil superposition principle, actual continuous cooling transformation can be calculated by isothermal transformation model. Here we discretize the whole time period into enough time steps, assuming that within each time step Δt, the temperature remains constant and the transformation is

isothermal transformation. Corresponding with each constant Ti, there are parameters b_i, n_i and transformation starting time, so-called incubation period τ_i. By dividing the time step Δt by incubation period τ_i, increment of inoculation rate ΔE_i can be obtained. When the accumulation of ΔE_i, i. e. namely inoculation rate E, reaches unity, the transformation starts.

During the transforming process, the transformed volumes could also be accumulated. Before deducing the transformed volume V_{i+1} under isothermal temperature T_{i+1}, the transformed volume during the former time step V_i should be put into **Eq.3** to get the time it takes for the transformed volume to reach V_i under T_{i+1} isothermal transformation condition, namely virtual time t^*_{i+1} .

$$t^*_{i+1} = [\frac{-\ln(1-V_i)}{b_{i+1}}]^{\frac{1}{n_{i+1}}} \tag{3}$$

With formula (1), the transformed volume of pearlite, bainite could be calculated by using $t_{i+1}=t^*_{i+1}+\Delta t$, and parameters b_{i+1}, n_{i+1} corresponding with T_{i+1}. After the temperature falls below martensite line, martensite volume can be calculated according to formula (2).

3.2. Calculation of microstructure field

From the start line and the end line in TTT curve of 42CrMo, we can get coordinates of a quantity of points, out of which the incubation time array $\{\tau\}$, array $\{b\}$, and array $\{n\}$ corresponding with temperature could be obtained by inverse calculation of transformation kinetics formula (**Eq.1**). Then, import these three arrays into ANSYS. Select time step Δt=1s, which should be short enough. Store the previously obtained temperature field result into another array. According to the block diagram shown in **Figure 4**, conduct secondary development in ANSYS via programming in APDL language to operate array calculation.

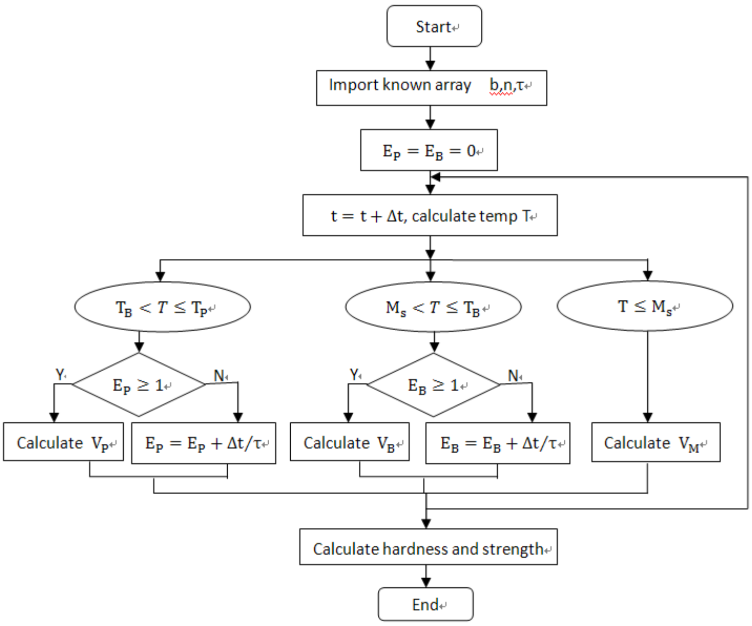

Figure 4. Program block diagram of microstructure field calculation

3.3. Mathematic model for hardness field

Hardness is a kind of property which is not sensitive to the arrangement of composites, but mainly determined by their contents and the hardness. Thus, the material hardness after quenching could be weighted average, according to the following formula.

$$X = \xi_M X_M + \xi_B X_B + \xi_F X_F + \xi_P X_P \tag{4}$$

where, X is the material hardness, ξ_M,ξ_B,ξ_F and ξ_P is the volume fraction of martensite, bainite, ferrite and pearlite, respectively, and X_M, X_B, X_F, X_P is the microhardness of martensite, bainite, ferrite and pearlite, respectively.

The microhardness of the same microstructure may vary a little due to the temperature and cooling speed when generated, and therefore the microhardness of each microstructure should be considered as a function of chemical element contents and cooling speed. This paper adopts **Eq.5~7** to calculate the microhardness of microstructures. These formulas fit more than 100 tests of more than 60 kinds of alloy steel according to study conducted by P. Maynier[8], and the dispersion is adequately small.

$$HV_M = 127 + 949C + 27Si + 8Ni + 16Cr + 21\lg V_r \tag{5}$$

$$\begin{aligned} HV_B = & -323 + 185C + 330Si + 153Mn + 65Ni \\ & + 144Cr + 191Mo + (89 + 53C - 55Si \\ & - 22Mn - 10Ni - 20Cr - 33Mo)\lg V_r \end{aligned} \tag{6}$$

$$\begin{aligned} HV_{F,P} = & \ 42 + 223C + 53Si + 30Mn + 12.6Ni \\ & + 7Cr + 19Mo + (10 - 19Si + 4Ni \\ & + 8Cr + 130V)\lg V_r \end{aligned} \tag{7}$$

where C, Si, Mn and so on represent contents of kinds of chemical elements respectively (%), V_r is the mean cooling speed at 700℃ (℃/h).

The metallographic structure content at different depths from the tread on line No. 1 in **Figure 1** is shown in **Figure 5**, in which, *VP*, *VB*, *VM*, and *VF* represent volume percentage of pearlite, bainite, martensite, and ferrite, respectively. The hardness distribution on line 1 is shown in **Figure 6**. As shown in **Figure 5**, after quenching, a large proportion of martensite could be produced at the surface part, where the thickness of hardening layer is a little more than 10mm; while the internal part is mainly bainite. Since the tread width of large-scale hydraulic steel gate is comparatively large, the microstructure distribution and hardness distribution of line 1 is quite like those of line 2. However, those factors on lines 3 are a little different from those of line 1, due to the fact that line 3 is closer to the boundary, where the temperature curve is different.

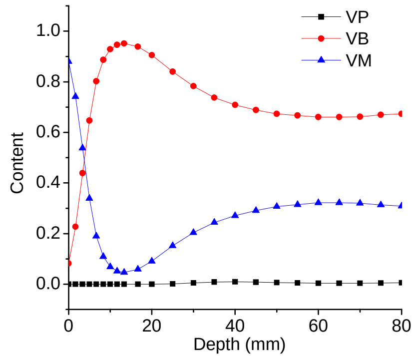

Figure 5. Microstructure content variation with depth

4. Analysis of the result of microstructure field calculation

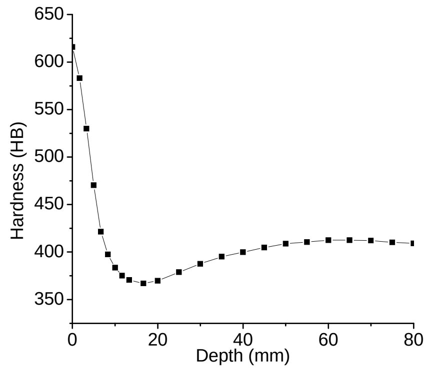

Figure 6. Hardness distribution under the tread

End quenching test is an important test which determines the hardenability and hardness after quenching. Yao Xin[9] got the water end quenching test results of P20 die steel. Make the P20 steel into φ25×200 cylinder, hold temperature at 860℃ to austenizing, isolate three sides, and then quench the bottom into 20℃ water. This paper simulated thermal field during P20 end quenching test. The measured value and calculated value are shown in **Table 2**. It suggests that, our method could simulate the quenching microstructure field appropriately.

Table 1. P20 end quenching test microstructure distribution

	Distance(mm)	Martensite	Bainite	Pearlite	Ferrite
Measured value	12.5	0.499	0.501	—	—
	90	—	0.838	0.162	—
	150	—	—	0.919	0.0811
Calculated value	12.5	0.518	0.478	—	—
	90	—	0.815	0.185	—
	150	—	—	0.887	0.113

As for the calculated results, the factors contribute to the deviation are manifold. Most important ones are 1) the deviation of TTT curve, 2) the over-simplified method to consider latent heat, 3)The TTT curve can not reflect the influence of high-temp produced composites on the transformation process during low-temp interval. Besides, the measurement precision of thermal physical parameters and surface heat transfer coefficient also have influences. Meanwhile, the experimental results also have deviation to some extent caused by not precisely controlled temperature and inaccuracy in microstructure measurement. From the comparison, we can conclude that the method adopted here could properly simulate the martensite and bainite content, while the pearlite content in the internal part is comparatively smaller than the actual situation. As for hardness distribution under the tread shown in **Figure 5**, the values within 20mm hardening layer is reliable, while the internal hardness is larger than the actual situation.

5. Conclusions

This work simulated temperature field of the large scale steel gate track during the quenching process, and obtained precise temperature field. With adopted mathematic model based on TTT curve, arrays calculation was performed by custom built computer program in ANSYS. The microstructure field of the track were calculated, as well as hardness, strength field. The result suggests that after quenching, up to 95% proportion of martensite was produced at the surface of track tread, where the thickness of hardening layer could be more than 10mm. The internal part gets about

70% bainite and 30% martensite, but the content of pearlite is really low. The hardness distribution is shown in **Figure 6**. With 19m·min^{-1} N32 quenching, superficial hardness of track tread could reach up to 606HB, and the superficial strength could reach up to 1130MPa. In order to meet the final track hardness requirements, it is proposed that the track should go through 300~350 ℃ low temperature tempering after quenching to reduce the hardness and strength loss.

6. ACKNOWLEDGEMENTS

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